Brain Computer Interfaces: An Introduction

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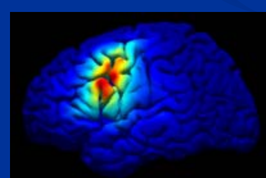
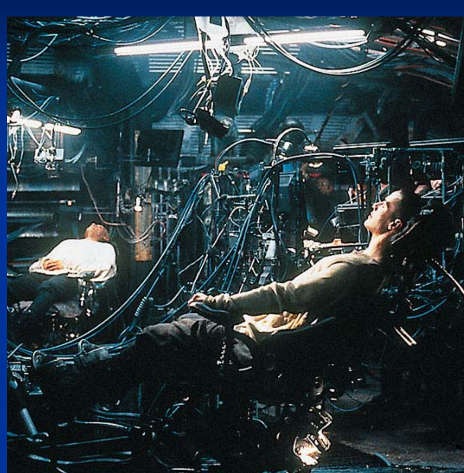
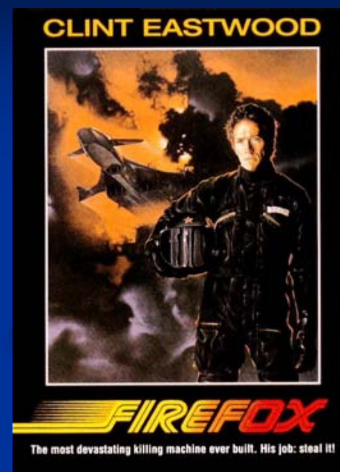




The Matrix (1999)

Johnny Mnemonic (1995)



Firefox (1982)

Brainstorm (1983)

Star Trek: The Next Generation

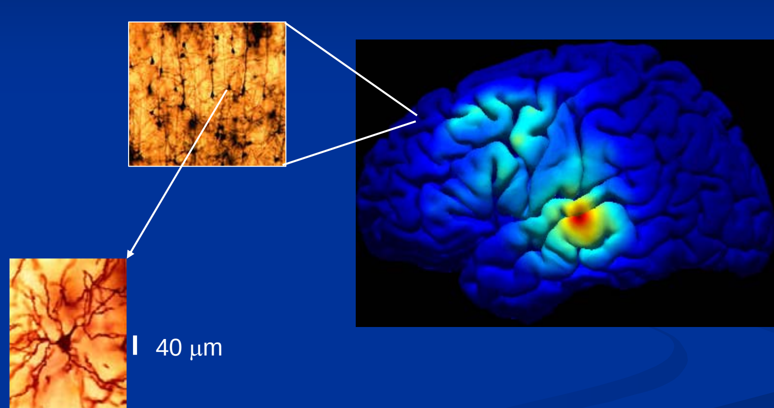
Spiderman 2 (2004)

Hollywood fiction or possible today?

Why would we want to engineer such devices?

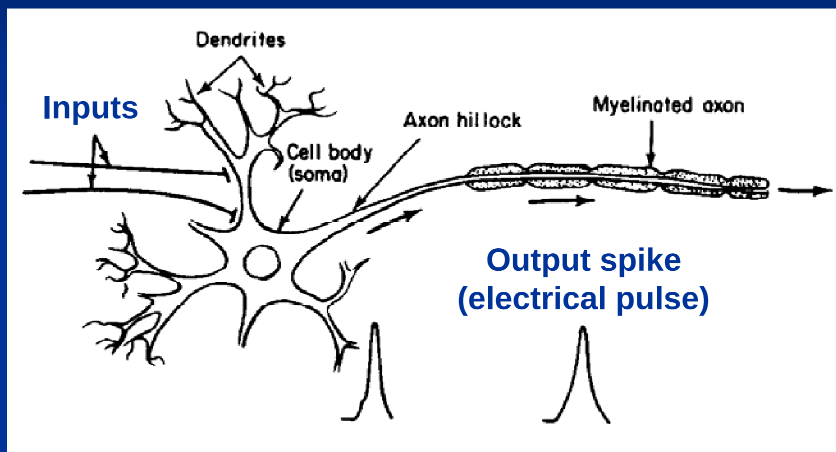
Can mathematics and engineering help people with such brain disorders?

The brain is comprised of networks of neurons (brain cells)

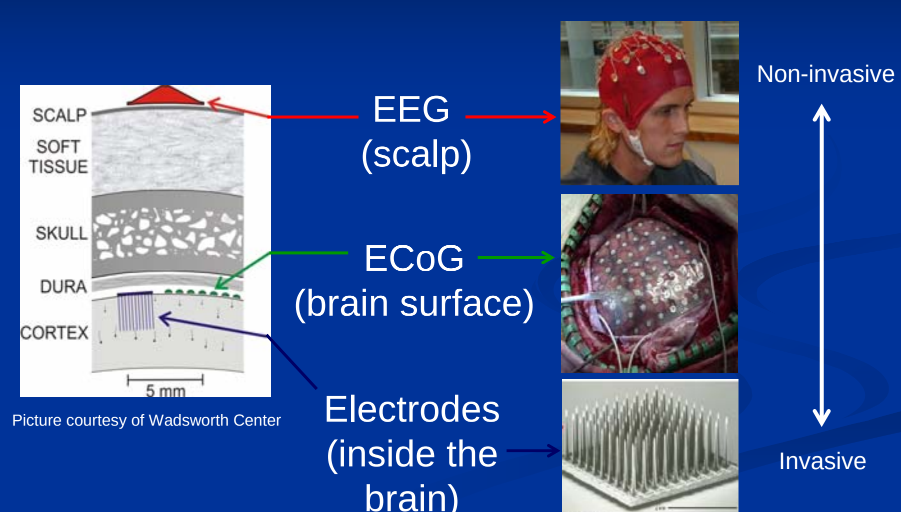


A Neuron

Neurons Communicate through Electrical Activity



The Brain's Electrical Activity can be Measured



Picture courtesy of Wadsworth Center

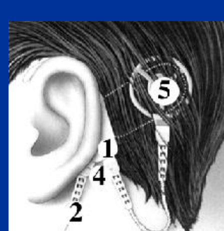
Electrical nature of the brain’s activity opens up the possibility of engineering devices for treating disorders

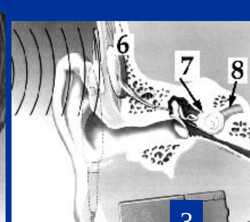
Devices may *record* brain activity and/or *stimulate* parts of the brain

Example: Cochlear Implants for the Deaf

Cochlear implants have improved hearing ability (in varying degrees) in a number of deaf children and adults

1. Microphone
2. Cable
3. Sound processor
4. Cable
5. FM radio transmitter

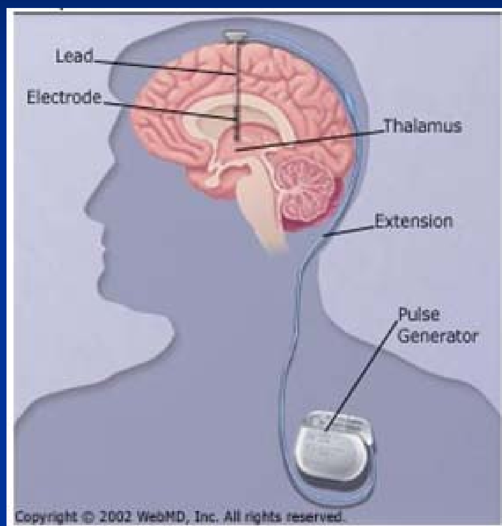




6. Receiver & Stimulator
7. Electrode array
8. Auditory nerve

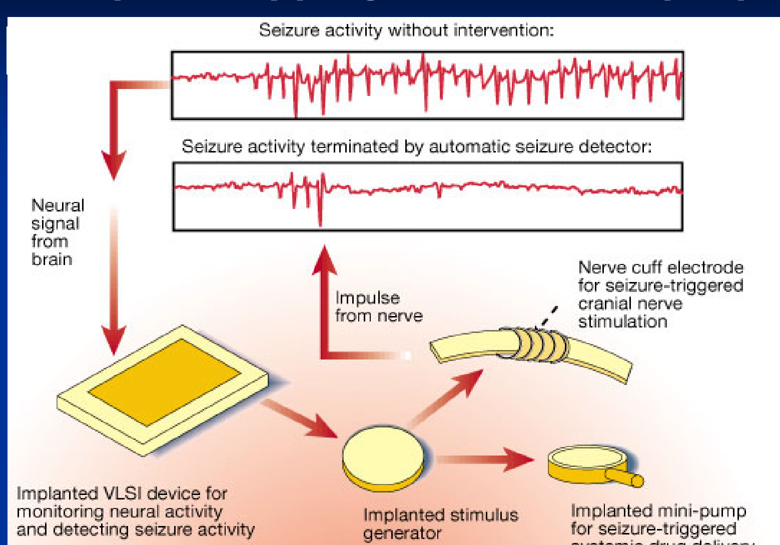
From: http://www.deafblind.com/cochlear.html

Example: Deep Brain Stimulation for Parkinson's Disease



Implanted device electrically stimulates parts of the brain to help reduce tremors, rigidity, and other symptoms

Example: Stopping Seizures in Epilepsy



(Nicolelis, 2001)

Such devices are examples of "brain-computer interfaces" or BCIs

Brain-Computer Interfaces

- **A Brain-Computer Interface (BCI)** is a device that records from and/or stimulates parts of the brain in order to:
  - Restore lost sensory capabilities (e.g., cochlear implants) or
  - Restore mental or motor function (e.g., epilepsy or Parkinson's) or
  - Significantly improve communication and control for paralyzed patients (e.g. stroke, ALS, spinal injury) or
  - Enhance sensory, mental, or motor capabilities in non-disabled individuals

Course Overview

- ***Today's Lecture*: Introduction to BCIs**
  - Basic components
  - Example BCI systems
- ***Tomorrow,* Feb 6: Basic Neuroscience and Machine Learning for BCI**
- ***Thursday,* Feb 7: Non-Invasive and Semi-Invasive BCIs**
  - EEG, fMRI, and ECoG-based systems
- ***Friday*, Feb 8: Invasive BCIs and Future Developments**
  - Electrode Arrays and Implants
  - BCIs: What lies ahead…

BCIs: The Hype

- Several commercial "BCI" systems exist
  - "Interactive Brainwave Visual Analyzer" (IBVA): "…trigger images, sounds, other software or almost any electronically addressable device…"
  - Cyberlink by Brain Actuated Technologies: "…operate computer software and any electrical device directly from the control center - *the mind*."
- Most are based on a *headband* with few sensors (typically 3)
- ***The Catch***: Control is more through eye movements and facial muscle activity than through brain activity

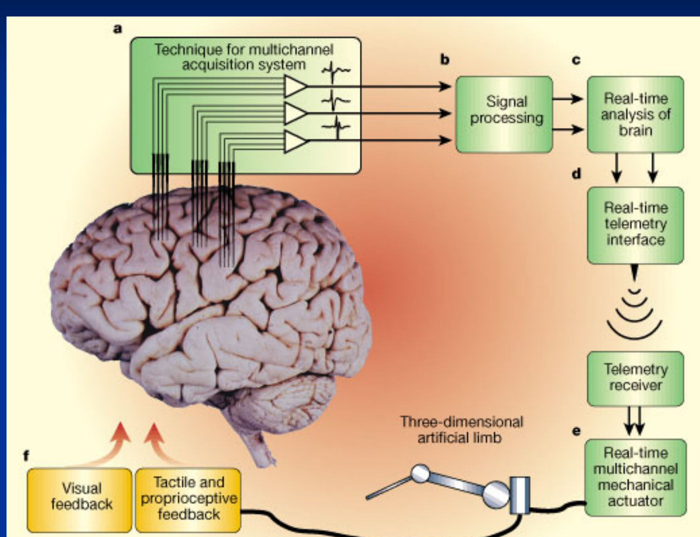
BCIs: More Hype

"Brain Fingerprinting"

http://www.brainwavescience.com/

"We use details that the person being tested would have encountered in the course of committing a crime. We can tell by the brainwave response if…a person has a record of the crime stored in his brain."

BCI: What is involved?

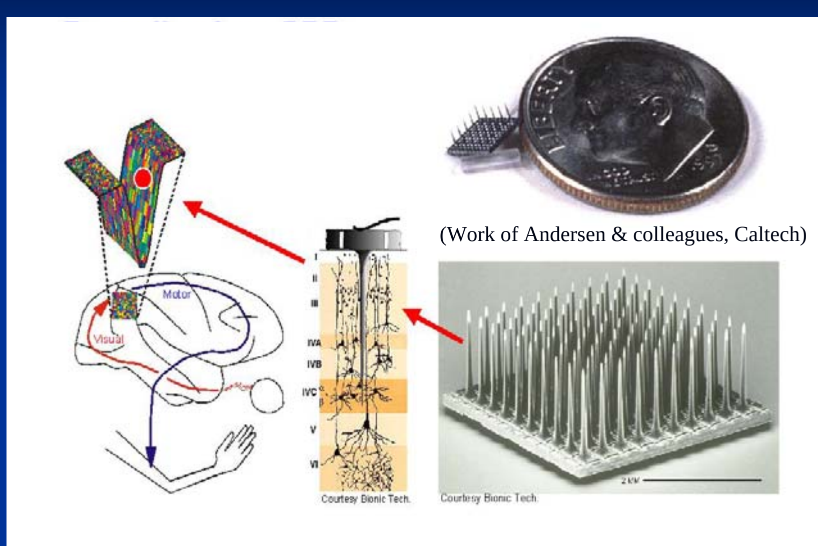


From (Nicolelis, 2001)

Invasive BCIs

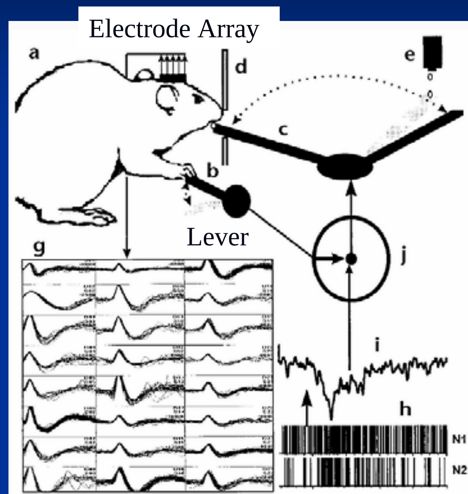
- Current Signal Acquisition Techniques:
  - Electrodes, Electrode Arrays, and Implants for recording and/or stimulating *inside the brain*
    - In animals (rats and monkeys) and some human patients (e.g., Parkinson's patients)
  - Surface Electrodes for recording electrical activity from the *brain surface* (Electrocorticography or ECoG)
    - In human patients scheduled for brain surgery

Example: Electrode Array



(Work of Andersen & colleagues, Caltech)

Example: BCI in a Rat



Water (Reward)

Robot Arm

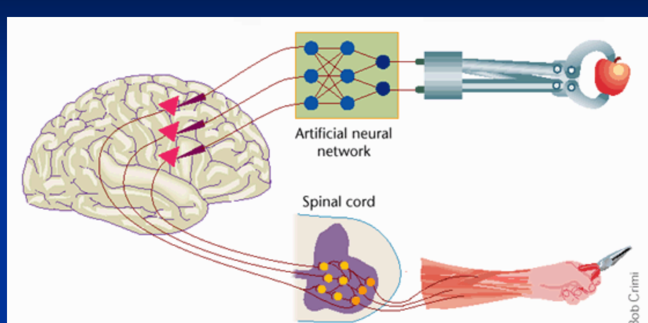
Switch to select between BCI/Lever Control

Recorded activities of 24 motor cortex neurons

Activity of 2 motor cortex neurons

(Chapin et al., 1999)

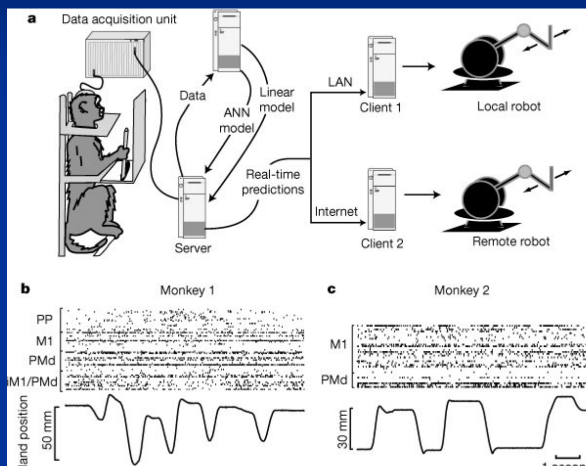
BCI in a Rat: Methodology



Experiment by Chapin et al., 1999:

- Rat presses a lever to move a robotic arm to get reward
- Neural outputs from rat's *motor cortex* train an artificial neural network to control the robotic arm
- After training, several rats no longer used their own body movements but retrieved reward using their neural activity

Example: BCI in a Monkey



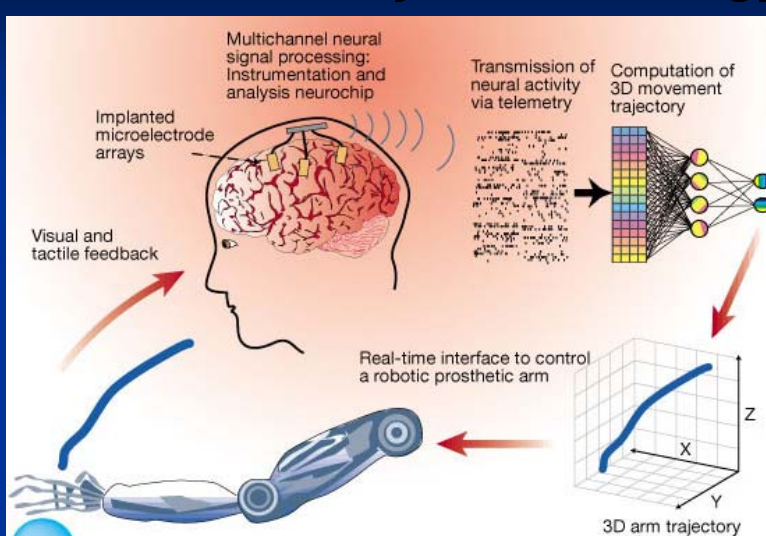
Experimental Set-Up

Spikes from neurons in several cortical areas in two monkeys

Hand Position

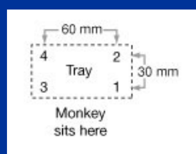
(Wessberg et al., 2000)

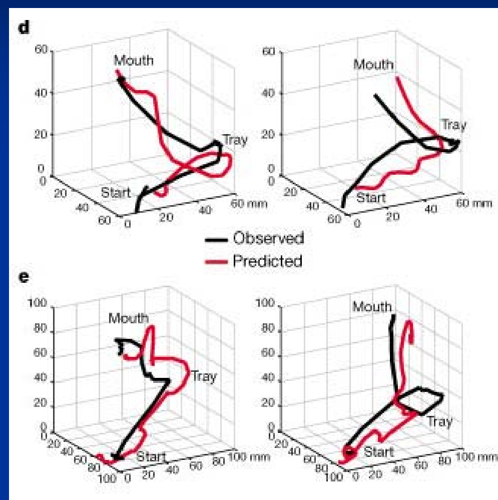
BCI in a Monkey: Methodology



(Nicolelis, 2001)

Results from Monkey BCI: Predicting Hand Movements





Hand Movement Sequence: Start → Food Tray → Mouth

(Wessberg et al., 2000)

Video: Monkey BCI controlling a robotic arm

(Work by Schwartz and colleagues, U. Pittsburgh)

http://motorlab.neurobio.pitt.edu/Motorlab/download_movies/download_movies.html

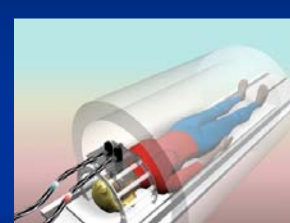
Invasive BCIs in Humans

- ECoG BCI: Electrodes placed on brain surface in patients scheduled for epilepsy surgery (U of Washington)
  - Control of cursors in 1D and 2D
- Brain Implant: Electrode array implanted inside the brain in a paralyzed patient (Brown U./Cyberkinetics Inc.)
  - Control of cursor and prosthetic hand

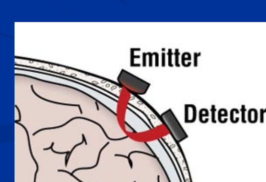
Non-Invasive BCIs: Current Approaches

Non-Invasive Recording Techniques

- Functional Magnetic Resonance Imaging (fMRI)
  - Measures changes in blood oxygenation levels due to increased brain activity
  - Good spatial resolution but too slow for real-time BCI



- Optical Brain Imaging (fNIR)
  - Also measures blood oxygenation
  - Slow for real-time BCI



Non-Invasive BCIs: Current Approaches

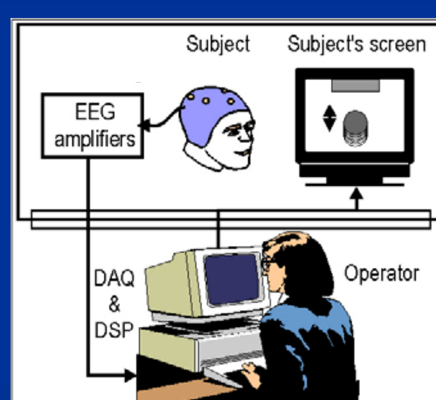
Non-Invasive Recording Techniques

- MEG (MagnetoEncephaloGraphy)
  - Measures changes in magnetic fields due to neural activity
  - Good spatiotemporal resolution but expensive and cumbersome

- EEG (ElectroEncephaloGraphy)
  - Measures voltage changes at the scalp due to neural activity
  - Good temporal resolution but poor spatial resolution
  - Cheap, hence commonly used in BCIs

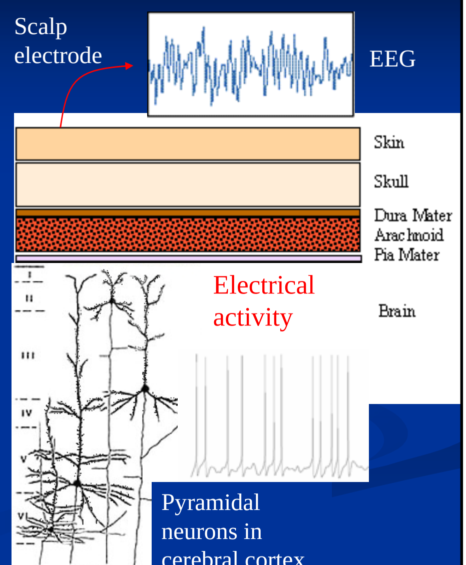
Non-Invasive BCIs: EEG-based Systems

- EEG signals: Acquired from a cap of electrodes that contact scalp through a gel
- Signals are in *microvolts* range → need to be amplified



What is EEG?

- Voltage fluctuations at the scalp due to activities of *large populations of neurons* in the cerebral cortex
- Input potentials and activities of neurons get attenuated and summated due to passage through meninges, cerebrospinal fluid, skull, and scalp



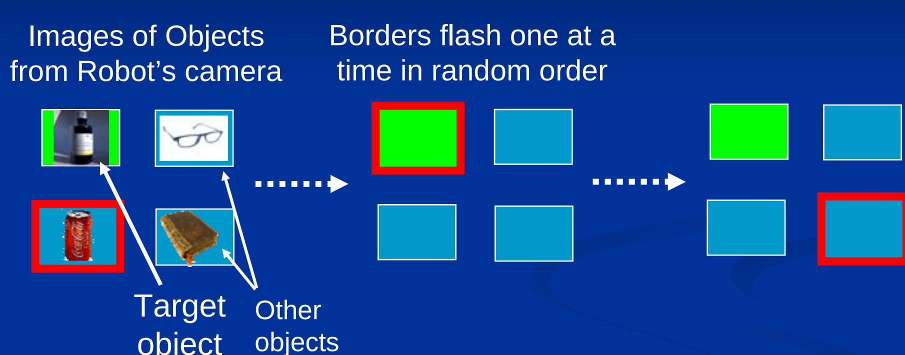
Some Achievements of EEG-based BCIs

- Typing words by flashing letters (Farwell & Donchin, 1988)
  - Select a character (out of 36) in 26 seconds with 95% accuracy
- Move a cursor towards a target on a screen by training subjects to control their EEG waves (Wolpaw et al., 1991; Pfurtscheller et al., 1993)
  - 10-29 hits/min and 80-95% accuracy after 12 45-min sessions
- Moving a joystick in 1 of 4 directions by classifying EEG patterns during mental tasks (Hiraiwa et al., 1993; Anderson & Sijercic, 1996)

Example Videos of EEG-Based BCI (from the Wadsworth Group)

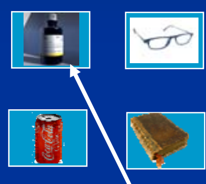
- A user controls a cursor to spell a word and select from icons in a menu (μ rhythm control, 64 channels EEG)
- An individual spells a word using visual evoked potentials

Using EEG to Select Objects

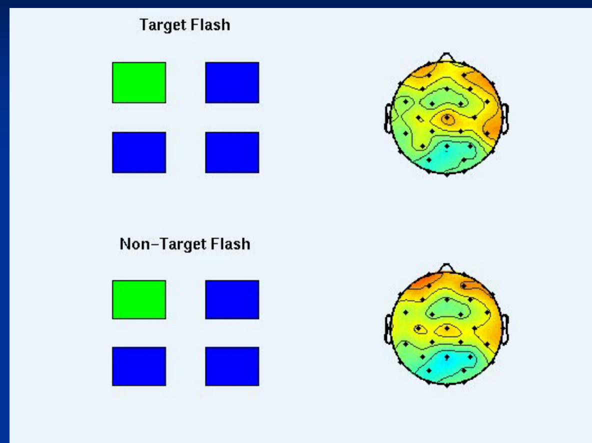


Evoked response (EEG) is different if flashed object is desired target object vs. a non-target object

Example of EEG Recognition Response



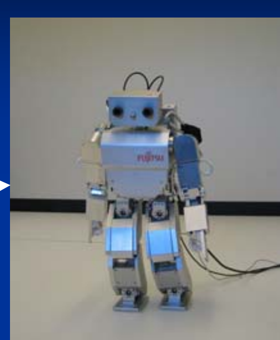
Target object



Support Vector Machine (SVM) classifies EEG responses

Example: EEG-Based Control of a Humanoid Robot

EEG command: “Go to kitchen”



Robot navigates to kitchen

EEG command: “Pick object X in camera image”

Robot picks selected object

EEG command: “Bring object to me”

Robot brings selected object

Direct Brain Control of a Humanoid Robot

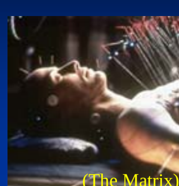
BCI Research: Current Problems and Challenges

- Signal Acquisition (Hardware): Need better technology to record activities of thousands of neurons with high signal-to-noise ratio
  - Non-Invasive BCIs: Need physicists to discover better methods of brain imaging than EEG/MRI
  - Invasive: Need biocompatible implantable chips for long term recording and/or stimulation of large groups of neurons
  - Need better instrumentation for amplification and telemetry

BCI Research: Current Problems and Challenges

- Signal Processing (Software):
  - Need more robust and adaptive algorithms for learning the mapping between brain activity and desired outputs
  - Algorithms need to be sensitive to noise and non-stationary statistics of brain data
  - Need co-adaptive systems that adapt in synch with human over long periods of time

BCI Research: Moral and Ethical Issues


(The Matrix)


(Terminator 2)


(Brazil)

- Privacy, safety, and health issues: What if someone:
  - “reads your thoughts”? “writes in new memories”?
  - sends a “virus” to an implant?
- Abuse of technology (in law, war, crime, and terrorism)
  - E.g. improper use of “brain fingerprinting”
- Societal impacts: The new haves and have-nots
  - Possession and control of BCIs to enhance mental/physical capabilities may significantly alter balance of power in society

Conclusions

- Significant advances are being made in the development of both non-invasive and invasive BCIs
  - Invasive systems in rats and monkeys can control robotic arms and cursors in real time for simple tasks
  - Non-invasive systems based on EEG allow reasonably accurate but slow control of cursors, robots, and spelling of words
- In the rest of the course, we will delve into these systems in more detail:
  - What are the brain signals being used?
  - What are the feature extraction and machine learning methods that underlie these systems?
  - What are the strengths and weaknesses of these systems?
  - What does the future hold in store?